

SUSY in the sky

or

keV signature of sub-GeV gravitino dark matter

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Abstract

We point out that recently discovered 3.5 keV line in X-ray spectra from various galaxy clusters and the Andromeda galaxy can be naturally explained by physics of a sector responsible for spontaneous supersymmetry breaking in models with R-parity. In this scenario the source of this line could be decay of sgoldstino - scalar superpartner of massive gravitino. At the same time the dominant dark matter component is stable gravitino whose mass is predicted to be about 0.25 GeV.

1 Introduction

Analysis of X-rays coming from galaxy clusters and from the Andromeda galaxy has revealed [1, 2] an anomalous signal at energy $E \approx 3.5$ keV. Although the observation has significance only at $(3\sigma - 4\sigma)$ level and its explanation in the framework of known physics is possible it would be very exciting if the source of this line is in new physics probably related to so far elusive dark matter. Various scenarios have been studied including sterile

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neutrinos [3, 4, 5], XDM model [6, 7], axion-like particles [8, 9, 10, 11, 12], millicharged particles [13] and light inflaton [14]. Below we are interested in possible explanations of this phenomena in the framework of supersymmetric theories. On this way there were considered scenarios with R-parity violation, where very long-lived dark matter particle of 7 keV decays into neutrino and photon, thus explaining the line at 3.5 keV. Light gravitino explanation [15] (see also [16]) needs quite low reheating temperature. Models with light axinos [17, 18, 19] are also quite tricky because they require quite small (less than 10 GeV) bino mass and other neutralinos to be considerably heavier.

In this paper we seek for the explanation in supersymmetric models *with R-parity*, so both proton and lightest supersymmetric partner are stable. We propose that sector responsible for spontaneous supersymmetry breaking (SSB) accounts for the 3.5 keV line and at the same time for dark matter. This sector contains goldstino, which becomes longitudinal component of gravitino in supergravity, and its superpartner(s). The latter in the simplest case are spin-0 bosons and are called sgoldstinos (for brief review on phenomenology of goldstino supermultiplet see [20]). We assume that the pseudoscalar sgoldstino (axion-like particle) has mass around 7 keV and gives observed in X-rays signal due to its decays into pair of photons (sgoldstinos are R-even and hence unstable). We calculate thermal production of sgoldstinos in early Universe and find that if we require that their two-photon decays explains 3.5 keV line in X-ray spectra sgoldstinos are always subdominant part of the dark matter. At the same time the dominant component is gravitino and it is interesting that the gravitino mass is also fixed in this setup and is about 0.25 GeV.

2 Setup

We start with presenting relevant interaction lagrangian (see e.g. [21, 25]) of pseudoscalar sgoldstino with gluons and photons

$$\mathcal{L}_P = \frac{M_3}{2\sqrt{2}F} P G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{M_{\gamma\gamma}}{2\sqrt{2}F} P F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad (1)$$

where $\tilde{F}_a^{\alpha\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\lambda\rho} F_{a\lambda\rho}^\alpha$ and $M_{\gamma\gamma} = M_1 \cos^2 \alpha_W + M_2 \sin^2 \alpha_W$, $M_{1,2,3}$ are soft gaugino masses and \sqrt{F} is supersymmetry breaking scale. Sgoldstinos also interact with quarks, leptons and other gauge fields, that we address later. Gravitino couples to other fields mostly through the longitudinal component, goldstino. Its interactions with other fields are given by derivative coupling to supercurrent

$$\mathcal{L}_{3/2} = \frac{1}{F} \partial_\mu \psi_{3/2} J_{\text{SUSY}}^\mu. \quad (2)$$

This approximation is valid up to energies $E \sim \sqrt{F}$. Sgoldstino with mass around 7 keV decays mainly into pair of photons and its lifetime is

$$\tau_P = \frac{32\pi F^2}{M_{\gamma\gamma}^2 m_P^3} \approx 1.9 \times 10^{27} \text{ s} \left(\frac{1 \text{ TeV}}{M_{\gamma\gamma}} \right)^2 \left(\frac{7 \text{ keV}}{m_P} \right)^3 \left(\frac{\sqrt{F}}{10^{10} \text{ GeV}} \right)^4 \quad (3)$$

If sgoldstino composes only a part of dark matter contributing a fraction ϵ to the present dark matter mass density, then the requirement that sgoldstino two-photon decay explains 3.5 keV X-ray line yields the following constraint

$$\tau_P \sim \epsilon \times (4 \times 10^{27} - 4 \times 10^{28}) \text{ s}. \quad (4)$$

The fraction ϵ should be not much smaller than 10^{-10} , otherwise τ_S is less than the age of the Universe and all relic sgoldstinos decay by present time. This implies the lower bound on supersymmetry breaking scale

$$\sqrt{F} \gtrsim 3 \times 10^7 \text{ GeV}. \quad (5)$$

3 Relic abundances of sgoldstino and gravitino

Let us continue with description of sgoldstino production in the early Universe. Assuming that the temperature is below the supersymmetry breaking scale \sqrt{F} we can expect that the main sources of this production are $2 \rightarrow 2$ reactions involving gluons g , gluinos \tilde{g} , quarks q and squarks \tilde{q} such as $gg \rightarrow gP$, $qg \rightarrow qP$, $\tilde{q}g \rightarrow \tilde{g}P$ etc. Boltzmann equation which describes evolution of sgoldstino number density reads

$$\frac{dn_P}{dt} + 3Hn_P = \gamma_P, \quad (6)$$

where H is Universe expansion rate and sgoldstino production rate γ_P has a form similar to that of the axion thermal production (see e.g. Ref. [23])

$$\gamma_P \approx \frac{\alpha_s M_3^2 T^6 \zeta(3)}{\pi^2 F^2} \beta, \quad (7)$$

where β is a factor of order unity and which has negligibly small dependence on plasma temperature T . For the axion-like particle production in the Standard Model this factor was estimated in the Hard Thermal Loop approximation [23] and more recently and accurately in [24] extending previous results to larger values of gauge coupling constants. In what

follows we take $\beta \approx 1$, so that numerical estimates of model parameters below are accurate up to a factor of few, which seems reasonable given the uncertainty in lifetime (4) following from observations [1, 2]. Using conservation of the entropy in co-moving volume, $s a^3 = \text{const}$ and relation $H = T^2/M_{Pl}^*$, where $M_{Pl}^* \approx M_{Pl}/1.66\sqrt{g_*}$ and $g_* \approx 229$ is effective number of degrees of freedom in supersymmetric plasma at high temperatures, Eq. (6) can be cast into the form

$$\frac{d}{dT} \left(\frac{n_P}{s} \right) = - \frac{\gamma_P M_{Pl}^*}{s T^3}. \quad (8)$$

The r.h.s of this equation does not depend on the temperature apart from mild changes in g_* at particle thresholds and running of strong coupling constant entering γ_P . Hence solution of Eq. (8) can be written as

$$\frac{n_P(T)}{s(T)} = \left(\frac{\gamma_P M_{Pl}^*}{s T^3} \right)_{T=T_R} \cdot (T_R - T) \quad (9)$$

where T_R is the reheating temperature. At sufficiently low temperatures obeying $m_{soft} \ll T \ll T_R$ where m_{soft} is the mass scale of superpartners one approximates

$$\frac{n_P(T)}{s(T)} = \left(\frac{\gamma_P M_{Pl}^*}{s T^3} \right)_{T=T_R} \cdot T_R. \quad (10)$$

Then sgoldstino number density at present time is

$$n_{P,0} = \frac{s_0}{s(T)} n_P(T) = n_{\gamma,0} \frac{g_*(T_0)}{g_*(T_R)} \frac{\beta \alpha_s M_{Pl}^* M_3^2}{2F^2} T_R \quad (11)$$

and for sgoldstino relative contribution to the present energy density of the Universe Ω_P one obtains following estimate

$$\Omega_P h^2 \approx 1.7 \times 10^{-8} \times \left(\frac{m_P}{7 \text{ keV}} \right) \left(\frac{M_3}{3 \text{ TeV}} \right)^2 \left(\frac{T_R}{1.7 \times 10^8 \text{ GeV}} \right) \left(\frac{10^{10} \text{ GeV}}{\sqrt{F}} \right)^4, \quad (12)$$

where $h \simeq 0.7$ refers to the normalized Hubble parameter. Similar contribution of relic gravitinos $\Omega_{3/2}$ was estimated in [22],

$$\Omega_{3/2} h^2 \approx 0.13 \times \left(\frac{M_3}{3 \text{ TeV}} \right)^2 \left(\frac{T_R}{1.7 \times 10^8 \text{ GeV}} \right) \left(\frac{10^{10} \text{ GeV}}{\sqrt{F}} \right)^2. \quad (13)$$

Comparing Eqs. (12) and (13) one can see that production of gravitinos is more effective and when mass density of gravitinos is sufficient to explain the dark matter the abundance

of sgoldstino is quite small: they form a subdominant fraction of the dark matter. Fraction $\epsilon \equiv \Omega_P/\Omega_{3/2}$ of produced sgoldstino checks with what constraint (4) gives if

$$\sqrt{F} \sim (0.8 - 1.2) \times 10^9 \text{ GeV} \times \left(\frac{m_P}{7 \text{ keV}} \right)^{2/3} \left(\frac{M_{\gamma\gamma}}{1 \text{ TeV}} \right)^{1/3}, \quad (14)$$

where we used the expression for sgoldstino lifetime (3). This implies gravitino mass $m_{3/2} = \sqrt{\frac{8\pi}{3}} \frac{F}{M_{Pl}} \sim (0.15 - 0.35) \text{ GeV}$. At the same time the requirement (13) that gravitino composes the dark matter determines the value of the reheating temperature

$$T_R \sim (1.0 - 2.4) \times 10^6 \text{ GeV}.$$

It exceeds the required value of the supersymmetry breaking scale (14), which justifies the use of effective lagrangians (1), (2) to describe sgoldstino and gravitino production in the early Universe.

4 Discussion and conclusions

To summarise, we present a supersymmetric model with two-component dark matter. The dominant part is gravitino with mass in sub-GeV region while the subdominant part is long-lived pseudoscalar sgoldstino. The latter decays into two-photons and can give rise to the unexplained excess in X-ray spectra at 3.5 keV [1, 2]. Note that we consider here pseudoscalar sgoldstino only as an example and scalar sgoldstino of 3.5 keV is not a worse candidate.

Actually both sgoldstinos are produced in the early Universe at the same rate provided they are lighter than \sqrt{F} . If both are sufficiently long lived their present abundances (c.f. (12)) are related as $\Omega_S = \frac{m_P}{m_S} \Omega_P$. If, say, pseudoscalar sgoldstino explains observed X-ray signal and $m_S \gtrsim 1 \text{ MeV}$ the scalar sgoldstino decays by the present epoch that may interfere with primordial nucleosynthesis and/or distort CMB spectrum. Lighter scalar sgoldstino contributes to present dark matter and similar to pseudoscalar sgoldstino its decay into pair of photons gives another X-ray line at energy $E_\gamma = m_S/2$. Given the same amount of sgoldstinos the expected X-ray fluxes from scalar Φ_γ^S and pseudoscalar Φ_γ^P are related as $\Phi_\gamma^S/\Phi_\gamma^P = m_S^3/m_P^3$ (see Eq. (3)). Observation of this second line provides an additional support to the suggested explanation of the X-ray excess at 7 keV.

Light gravitino and sgoldstinos are natural in e.g. models with gauge mediation of supersymmetry breaking [26, 27] which elegantly circumvent experimental bounds on SM superpartner mass scale from studies of flavor and CP-violation. However, the adopted hierarchy

between sgoldstino and gravitino masses is not typical. Let us illustrate this issue with a toy model of goldstino superfield $X = \phi_X + \sqrt{2}\theta\psi_{3/2} + \theta^2 F_X$ and superpotential $W = -FX$, which triggers supersymmetry breaking. The Kähler potential is

$$\mathcal{K} = X^\dagger X - \frac{\alpha}{4M^2} (X^\dagger X)^2 - \frac{\beta}{6M^2} (X^\dagger X^3 + X^{\dagger 3} X), \quad (15)$$

where the last two terms model corrections from hidden sector and from mediator and gravity interactions. These terms are suppressed by some energy scale M and α, β are some constants. After supersymmetry breaking $\langle F_X \rangle = F$ and decomposing $\phi_X = \frac{1}{\sqrt{2}}(S + iP)$ one obtains for sgoldstino masses

$$m_S^2 = \frac{F^2}{M^2} (\alpha + \beta), \quad m_P^2 = \frac{F^2}{M^2} (\alpha - \beta). \quad (16)$$

Comparing them with gravitino mass one can see that given $M \lesssim M_{Pl}$ the hierarchy $m_P \ll m_{3/2}$ implies either a smallness of α and β or strong degeneracy between their values. Models of this kind have been considered for example in Refs. [28, 29, 30] however in a different context. Dark matter gravitino of sub-GeV mass has been also discussed in literature, see e.g. [31]. The values of model parameters required for the suggested explanation of 3.5 keV line are consistent with present astrophysical, cosmological and phenomenological bounds on goldstino sector [20]. We have checked also that for the scale of SUSY breaking (14) lifetime of superpartners of SM particles is small enough ($\lesssim 0.1$ s) for these species to interfere with the primordial nucleosynthesis. Successful production of gravitino and sgoldstino by scattering of particles in primordial plasma implies the Universe reheating temperature $T \sim 10^6$ GeV, that seems to leave enough room for baryogenesis in particular realizations of the suggested scheme.

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